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The Impact of Different Particle Sizes of Phosphorus Fertilizers on Wheat (*Triticum aestivum* var. Egypt 3) Yield, Nutrient Uptake and Soil Phosphorus Availability

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AGRICULTURE is fundamental to ensuring global food security, with enhanced crop production being crucial. Phosphatic fertilizers serve an important role in sustaining agricultural productivity and meeting the needs of an expanding population. A field experiment was conducted to assess the effects of phosphorus fertilizer [ordinary superphosphate (OSP) and rock phosphate (RP)] with different particle sizes (without sieving, 1.0-0.5, 0.5-0.25, 0.25-0.125 and <0.063 mm) using loamy sand soil on the straw and grains yield of wheat, the content of NPK in the grains and the availability of phosphorus in the soil. The results indicated that the maximum straw and grain yields were reached for OSP (10.9 and 8.59 Mg ha^{-1}, respectively) and RP (8.39 and 6.64 Mg ha^{-1}, respectively) in soil treated with 1.0-0.5 mm particle size for both P fertilizers. The highest residual soil P (18.5 mg kg^{-1} for OSP and 23.9 mg kg^{-1} for RP) were observed in treatments with <0.063 mm particles. A highly negative correlation (r = -0.97 for OSP; r = -0.92 for RP) was observed between residual soil P and particle sizes of fertilizer. The results revealed that the maximum uptake of NPK was recorded in treatments 1.0-0.5 and 0.5-0.25 mm compared to whole fertilizers. The addition of RP significantly increased soil P (19.8 mg kg^{-1} soil) compared to OSP treatments (15.6 mg kg^{-1} soil). It could be concluded that the segregation of P fertilizer is essential for enhancing soil P and maximizing wheat yield, providing valuable insights for agricultural practices in similar soil conditions.

Keywords: Phosphorus fertilizers, Particle size, Wheat, Uptake, Soil phosphorus.

Introduction

Agriculture plays a major role in improving food security and nutrition through food diversity and increasing quantity and providing the primary source for many of the world population **(Mahmoud *et al.,* 2024)**. The demand for increased agricultural productivity from strategic crops such as wheat has never been more necessary now as global population estimates indicate that the world population has arrived to 9.7 billion by 2050 **(Teng, 2024)**. Phosphorus (P) is one of the important nutrients for the plant and is an essential element of fertilization that strongly affects plant growth and yield of crops **(Khan *et al.,* 2023)**. The soils in their natural state usually do not contain a sufficient amount of P suitable for plant nutrition to produce the greatest crop due to its unavailability in the alkaline soils containing calcium ions or in acidic soils containing iron and aluminum ions **(El Attar *et al.,* 2022)**. Rock phosphate is the major source of P fertilizer; yet, it is a finite, non-renewable mineral resource **(Samreen and Kausar, 2019)**. Various cereal crops, particularly wheat, benefit from P applications, as it is essential for root development, energy transfer and photosynthesis **(Renjith *et al.,* 2020)**. When fertilizing with manufactured P fertilizers, only 25-30% of the added P is available to absorb the plant and the rest is converted into un- available and insoluble form, the release of which depends on the characteristics of the soil **(Aziz *et al.,* 2015)**. Egypt's alkaline agricultural soils have a distinct set of difficulties for crop development, particularly regarding P element, which has a major impact on the productivity of alkaline soils **(El- Naqma *et al.,* 2024)**. Tricalcium phosphate ($Ca_3(PO_4)_2$), as insoluble inorganic form of P that is impossible for plants to utilize, accumulates in Egyptian soils, where the pH of the soil can increase above 7.5 to 8.2 **(El-Ramady *et al.,* 2019)**. The efficiency of phosphate fertilizers depended on several factors, such as the particle sizes of the fertilizer. This study hypothesis that phosphate fertilizers with optimized particle size can improve wheat yield and P availability under arid loamy sand soils. This is very crucial for enhancing fertilizer use efficiency and providing guidance to phosphate fertilizer industries on producing the optimal particle sizes of fertilizer.

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Optimizing the application of fertilizers, based on the research findings, can reduce both the financial burden on farmers and the environmental degradation caused by over-fertilization, aligning with sustainable agricultural practices and supporting climate action goals. The impact of type of P fertilizer on soil P availability and crop yield. However, on the other hand, **Rakita *et al.*, (2023)** suggested that the impact of granule size on wheat yield depended on several factors such as soil type, moisture levels, and crop management practices.

Research of the literature revealed a few studies which were conducted to investigate the impact of size distribution of phosphate fertilizer granules on P availability and plant production. Therefore, the objective of this study was to evaluate the influence of particle sizes of ordinary super phosphate and rock phosphate on the availability of P in the soil. The effect of phosphate fertilizers with different particle sizes on wheat yield components (straw and grains) and nutrient uptake (NPK) in grains under field conditions was also investigated.

Materials and Methods

Characterization of the study area

The study area occupies the Ismailia Governorate, between longitudes 31º 41' 25.56" and 32º 21' 20.72" E and latitudes 30º 28' 50.39" N and 30º 54' 53.95" N. It is bordered from the north and west by the northern and western boundaries of Ismailia Governorate and from the east by the Suez Canal. The entire territory of El-Ismailia Governorate is in a zone that is affected by long, dry, and hot summers and short, nearly rainless and cold winters. The region has an average annual temperature of 22˚C, with July exhibiting the highest temperatures (maximum 38˚C) and January the lowest (minimum 8˚C). The soil temperature regime is classified as hyperthermic, whereas the soil moisture regime is predominantly aridic (torric), with aquic conditions occurring in areas with elevated water tables. The mean annual relative humidity is 51.4%, reaching its peak at 60% in December and declining to 42% in May. These climate conditions exert a considerable influence on soil qualities and agricultural productivity within the region **(Amira *et al.*, 2021)**.

Experimental design and treatment applications

A field experiment was conducted in Sarabium, Ismailia governorate, Egypt, in two stages because the soil (loamy sand) was used in this experiment was high available P (11.66 mg kg^{-1}). Therefore, the first stage aimed to deplete available soil P before starting the field experiment. The second stage is to assess the influence of particle sizes of phosphate fertilizers on wheat yield, nutrient uptake, and soil P availability.

First stage: depletion of phosphorus from soil

The experiment was conducted to reduce available P values in the soil. In this field experiment, thirty plots (4 m x 2 m) were used with three replications. The soil was cultivated with corn plants (*Zea mays* var. Pioneer 3080) from May 2023 to August 2023 under a drip irrigation system. Corn plants were used in this experiment because they are intense, short-cycle development and require higher amounts of P during their cultivation. The plants were fertilized only with N and K and without addition P fertilizer as recommended by the Ministry of Agriculture for corn in Ismailia governorate. In addition, cattle manure (20 m^3 fed^{-1}) was also added as organic fertilizer for all plots during the preparation of soil. After harvesting the corn, approximately 20 soil samples were collected to estimate the available P in the soil. The results indicated that the mean of available P in the soil reached 7.12 mg kg^{-1} after P depletion experiment. Based on this result, the second stage of field experiment will start.

The second stage of wheat field experiment

A field experiment was conducted in Sarabium, Ismailia, to assess the impact of different particle sizes of phosphatic fertilizers, specifically OSP and RP, on wheat yield (*Triticum aestivum* var. Egypt 3), P availability, and the concentration of N, P, and K in grains under a sprinkler irrigation system. The experiment was conducted from December 2, 2023, to April 20, 2024, for a single winter season in 2023-2024. In this experiment, thirty plots (4 m x 2 m) were used, and the experiment was designed in a complete randomized block design (CRBD) with three replications. Phosphate fertilizers, namely ordinary superphosphate (OSP, 15.5% P_2O_5) and rock phosphate (RP, 21.6% P_2O_5), were used with five different diameters and applied before cultivation for each plot. The recommended full dose of OSP and RP fertilizers was applied via broadcast method, following guidelines set by the ministry of agriculture, at a rate of 31 kg P_2O_5 per fed^{-1}. The experiment was composed of five treatments as follows: without a sieve (T1), 1.0-0.5 mm (T2), 0.5-0.25 mm (T3), 0.25-0.125 mm (T4), and less than 0.063 mm (T5). Depending on climate and length of the total growth season (120 days), wheat required between 450 and 650 mm of water. From establishment to flowering, evapotranspiration increases and can exceed 5 to 6 mm/day. A composite soil sample was randomly collected from the study area prior to cultivation for comprehensive physical and chemical analyses (Table 1). Additionally, cattle manure was subjected to analytical evaluation, following methodologies described by **Klute (1986); Sparks *et al.* (2020)**. The experiment was irrigated with well water, and the properties of water are shown in Table 2 **(Sparks *et al.*, 2020)**.

Nitrogenous fertilizer was applied as ammonium sulfate, containing 20.5% nitrogen, in three installments, 20%, 30%, and 50% of the total dose at a rate of 100 kg N per fed^{-1}, administered 21, 30, and 60 days after sowing. Potassium fertilizer, in the form of potassium sulfate (50% K_2O), was uniformly applied in two doses across all plots at a rate of 50 kg K_2O per fed^{-1}. After 120 days of growth, corresponding to the ripeness stage, wheat plants were harvested **(Ghanem *et al.,* 2013)**. The yield components, including grain and straw yield, were systematically recorded. Additionally, soil samples were collected from each experimental plot for past-harvest P availability analysis, following the **Murphy and Riley (1962)** method.

Soil analyses Using a Jenway 3510 pH meter soil pH was measured, with soil-water suspensions prepared at a 1:2.5 ratio. Using 2.0 M potassium chloride available inorganic N was extracted, following the Kjeldahl method **(Bremner, 1996)**. The available inorganic P was quantified spectrophotometrically using a Jenway 6105 spectrophotometer, with 0.5 M $NaHCO_3$ soil extract at pH 8.5, according to the Olsen method **(Kuo, 1996)**.

Table 1. Selected physical and chemical properties of soil used in this study (Second stage) and cattle manure (CM) used in first stage.

Properties	Soil	CM
Particle size distribution, %		
Sand	80.12	-
Silt	5.65	-
Clay	14.23	-
Textural class	Loamy Sand	-
Bulk density, g cm^{-3}	1.39	-
Soil order	Aridisols	-
Field Capacity (%)	23.4	-
EC_e (dS m^{-1}) §	2.30	10.2
pH	7.59†	7.40‡
Soluble cations (mmol /L) §		
Ca^{++}	5.60	13.5
Mg^{++}	4.08	5.15
K^+	0.19	30.0
Na^+	3.40	34.2
Soluble anions (mmol /L) §		
HCO_3^-	8.50	32.1
Cl^-	6.87	48.4
SO_4^{--}	3.81	10.6
Organic C, g kg^{-1}	5.53	144
Available P, mg Kg^{-1}	7.12	122
Available N, mg kg^{-1}	5.76	125
Available K, mg kg^{-1}	135	-
Total P, g kg^{-1}	1.28	5.12
Total N, g kg^{-1}	0.14	11.5
$CaCO_3$, g kg^{-1}	27.5	-

§In CM and soil saturated extract, †In soil-water suspension (1:2.5), ‡In CM-water suspension (1:5)

Table 2. Some chemical composition of well water that are used in irrigation.

EC dS m^{-1}	0.42
pH	7.28
Ion's concentration, (mmol /L)	
Ca^{++}	0.88
Mg^{++}	0.40
Na^+	1.33
K^+	0.20
HCO_3^-	1.64
CO_3^{--}	0.00
Cl^-	2.25
SO_4^{--}	0.09
SAR	1.17
Water class	C_2S_2

Plant analyses

Using the Kjeldahl method, the total N content in wheat grains was quantified, a standard procedure for nitrogen determination in biological samples. Briefly, the wheat grains were grinding and wet digestion using concentrated sulfuric acid and hydrogen peroxide (H_2O_2) **(Bremner, 1996)**. While a nitric (HNO_3), sulfuric (H_2SO_4), and perchloric ($HClO_4$) acid combination (4:1:8 v/v) was used for wheat grains wet digestion and to measure the P and K contents. A spectrophotometric measurement of P was then made using the molybdenum-blue method, and K was measured using a flame flamephotometer **(Sparks *et al.,* 2020)**.

Statistical analyses

Analysis of variance (ANOVA) was performed on all collected data using **(Co Stat Software, 2005)**, Version 6.311 (Cohort Program). The least significant difference test (LSD) ($P<0.05$) was used to compare the treatment means. The SPSS Program Version 19.0 was used to calculate the correlation between the parameters studied according to **Snedecor and Cochran (1982)**.

Results and Discussion

Impact of particle size of phosphate fertilizers on wheat yield

The influence of phosphate fertilizers particle size on wheat yield was assessed over a 120-day trial as shown in Tables 3 and 4. The obtained results indicated that significantly increase in straw, grain, and biological yields with particle size segregation treatments. Treatments T2 (1.0-0.5 mm) and T3 (0.5-0.25 mm) showed the highest yields for grain across both fertilizers (Tables 3 and 4). Maximum straw and grain yields were recorded for OSP (10.9 and 8.59 Mg ha^{-1}, respectively) and RP (8.39 and 6.64 Mg ha^{-1}, respectively) in plots treated with 1.0-0.5 mm particle size. Similarly, biological yield was highest in plots receiving segregated particles between 0.25 and 1.0 mm for both fertilizers. No significant differences were observed in the grain-to-straw (G/S) ratio for all treatments. There is a significant increase in grains and straw when using different particle sizes between 1.0-0.5 and 0.5-0.25 mm compared to the other particle sizes used and the control (whole fertilizer or no sieve fertilizer). Phosphorus availability in Egyptian soils is extremely limited, primarily due to the high soil pH, which significantly reduces P activity and mobility. Furthermore, the type of phosphate supply plays a critical impact in determining soil P availability, directly influencing crop productivity and nutrient uptake efficiency. Therefore, for alkaline soils, fertilizers are required to be selected that can sustain P activity for a long time. The results indicated that the maximum straw and grain yields were recorded for OSP treatment when compared to RP treatment. This result can be attributed to the greater solubility of OSP relative to RP, this improves P availability in the soil and facilitates absorption by plants. Treatments T2 (1.0-0.5 mm) and T3 (0.5-0.25 mm) showed the highest yields for grains for both fertilizers. These results can be clarified primarily by applying segregation particle size for P, resulting in an increase in contact time between soil particles and particle size of phosphate fertilizer, thus decreasing the accessibility of P in the soil owing to some factors such as fixation and immobilization **(Costa *et al.,* 2022)**. Particle size of P fertilizer influences the utilization of applied P in two ways. *First*, it affects the distribution of fertilizer in soil, *Secondly,* the effective surface area and therefore the reactivity of P fertilizer with soil, which affects availability **(Bindraban *et al.,* 2020)**. To reduce the rates of phosphate fertilizer, use and their impact on the soil while increasing their efficiency, and crop yield. Improved microenvironments can be used such as fertilizer granules and nutrient abundance. The use of these microenvironments leads to increasing farmers income and achieving sustainable development goals, so the separation of phosphate fertilizer granule sizes depends on several factors such as the type of soil and its characteristics as well as the surrounding environmental conditions, The outcomes are consistent with those published by **Wang *et al.,* (2025)**. Increasing P fertilizer application to wheat caused an increased number of tillers, grain yield, number of grains per spike and plant height. Many metabolic activities for response crops affecting by deficient in P and N soil. Previous studies found that the time of application plays an important role in increasing P efficiency and crop yield **(Elhag, 2023)**. Fine granules play an important role in retaining P necessary for plant absorption with the availability of the necessary conditions for its long-term availability within the soil. Because of this the process of separating fertilizer granule sizes has a significant effect on the availability of P in the soil. All these practices and strategies to separate phosphate fertilizer granules into different sizes led to an increase and improvement of wheat growth, which was reflected in increasing crop productivity while maintaining soil fertility in the long term under the same conditions for crops grown later as a result, it leads to a high concentration of nutrients in the soil and enhances the fertility and sustainability of the soil **(Spohn, 2020)**.

Effect of phosphorus fertilizer particle size on past-harvest soil available P

Following wheat harvesting, the remaining available P content in the soil was considerably affect by the segregation particle size of applied phosphate fertilizers, including OSP and RP. Figures 1 and 2 show that soils treated with segregated phosphate fertilizer particles had higher residual P compared to the control (whole fertilizer or no sieve fertilizer). The highest residual soil available P concentrations (18.5 mg kg^{-1} for OSP and 23.9 mg kg^{-1} for RP) were observed in treatments with <0.063 mm particles. That is, smaller granules exhibited greater solubility, resulting in higher residual P levels. Correlation analysis revealed a highly negative relationship between segregation particle size and residual P concentration for both fertilizers (r = -0.97 for OSP; r = -0.92 for RP). Furthermore, a highly positive correlation (r = 0.88) was identified between residual P levels and the phosphate fertilizer type. These findings indicate that finer fertilizer particles improve P availability, whereas coarser particles demonstrate reduced solubility yet contribute to extended residual effects in the soil. This study aimed to evaluate the effect of separating phosphate fertilizer granule sizes on the availability of P for plant absorption and the results obtained indicated that the separated granules of different sizes contain more P than whole fertilizer, which led to an increase in the concentration of P in the soil solution, which affects the mobility and absorption of nutrients **(Yang and Yang, 2021)**. This study underscores the importance of tailoring phosphate fertilizer particle sizes to optimize both immediate and residual P availability in soils, supporting sustainable agricultural practices **(Jahan *et al.,* 2025)**. The remaining available P in soils treated with finer phosphate fertilizers has decreased over time, highlighting the importance of balancing the immediate availability of P with long-term sustainability. In addition, research suggests that P fixation occurs mostly in soils with a fine texture, where a larger surface area provides more binding sites for P ions **(Zhang *et al.,* 2025)**. The use of phosphate-solubilizing bacteria and organic matter and has significantly increased the availability of P in the soil. This effect is likely attributed to the release of organic acids caused by organic matter, which contribute to reducing soil pH compared to coarse particles. Previous studies have confirmed that while fine particles may initially increase the available P, the remaining long-term effects depend on soil properties. For example, on acidic soils, P can be precipitated with iron and aluminium, which reduces its availability depend on the size of particles. Conversely, in alkaline soils, P may bind to calcium, which similarly affects its long-term availability. This residual P may remain available in the soil for subsequent crop seasons, enhancing nutrient utilization efficiency. Organic matter or acids can facilitate the release of P from small grains, making them easily absorbable by plants. In contrast, larger granules showed low interaction with the soil, reducing stabilization or precipitation but limiting immediate plant availability and dissolving phosphate fertilizers, especially RP. **(Kanagalabavi *et al.,* 2025)**.

As a result, the bioavailability of phosphate-solubilizing bacteria is improved for plant absorption, thereby enhancing the efficiency of phosphate fertilizers **(Pang *et al.,* 2024)**. This was especially pronounced for RP, which benefits from soil moisture retention and the release of organic acids, resulting in improved solubility and absorption efficiency. In addition, inoculation with phosphate-solubilizing bacteria accelerated the decomposition of organic matter and the release of P-soluble organic acids. This effect has been achieved by improving the efficiency of phosphate fertilizers, in particular phosphate fertilizers, thereby facilitating the further solubility and absorption of P by plants **(Alzubaidi and Abed, 2024)**.

Effect of phosphorus fertilizer particle size on N, P, and K content and uptake in wheat grains

The study found that the particle size segregation of phosphate fertilizers greatly improved the uptake of N, P, and K in wheat grains compared to the control (whole fertilizer). Treatments T2 (1.0-0.5 mm) and T3 (0.5-0.25 mm) demonstrated the highest nutrient uptake across all parameters. Ordinary superphosphate resulted in greater nutrient absorption (248 kg ha^{-1} N, 34 kg ha^{-1} P, 119 kg ha^{-1} K) than RP, which showed lower but notable nutrient uptake (191 kg ha^{-1} N, 24 kg ha^{-1} P, 89.5 kg ha^{-1} K) (Tables 5 and 6). Statistical analyses confirmed high positive correlations ($P < 0.001$) between nutrient uptake and yield components, indicating that segregated particle size application enhances nutrient use efficiency and wheat productivity. Phosphate fertilizers raise wheat when P levels rise. The proper quantity of balanced fertilizer for wheat, however, affects the plant's uptake of P in addition to increasing production. The results of this study reveal that the particle size of phosphate fertilizers has a crucial role in improving the N, P and K content and uptake in wheat grains. Maximum uptake of N, P and K was recorded in treatments T2 (1.0-0.5 mm) and T3 (0.5-0.25 mm) compared to the use of whole fertilizers, highlighting the value of fine particle sizes in enhancing nutrient availability and absorption. The fine particle size of phosphate fertilizers led to an increase in P absorption in wheat compared to coarse particles. The results emphasize the need to provide P fertilizers with optimal particle sizes to increase nutrient absorption and crop productivity. Soil texture and pH significantly affect the efficiency of different particle sizes of phosphate fertilizers **(Boubekri *et al.,* 2023)**. The yield of wheat grains was significantly and positively associated with P absorption. According to the results, the consumption of P-containing plants enhances their production and uptake by activating the root system, increasing cell division, forcing the plant to bloom by regulating N uptake **(Ali and Akmal, 2022)**. Moreover, these conclusions correspond to previous studies, which indicated better nutrient availability with optimal fertilizer utilization. Wheat grains enriched with fine phosphate molecules included greater amounts of key nutrients, such as N, K, and P. In addition, research suggests that the size of phosphate fertilizer particles plays a key role in controlling their rate of dissolution, ultimately affecting the availability of P in the soil for plant uptake **(Gong *et al.,* 2024)**.

Smaller phosphate fertilizer particles exhibit a larger surface area, which enhances the rate of P dissolution, thereby improving the availability of nutrients for plant absorption. In contrast, larger particles dissolve at a slower rate, resulting in a decrease in the bioavailability of P for crops. Maize and wheat crops showed significant yield increases when fertilized with OSP compared to RP **(Hamissa *et al.,* 2023)**. The need to modify the properties of phosphate fertilizers to increase crop productivity and soil fertility. This research highlights the potential for improving fertilizer use methods that improve the nutritional quality of wheat **(Liang *et al.,* 2024)**. Based on a statistical analysis of the data used for the present study, there are significant positive correlations between the grain yield components and N ($r = 0.88^{**}$), P ($r = 0.97^{**}$), and K ($r = 0.92^{**}$). There was a positive and substantial correlation between the available P and the following: P concentration in grain ($r = 0.666^{*}$ to 0.749^{*}), total P uptake ($r = 0.860^{**}$ to 0.928^{**}), grain yield ($r = 0.829^{**}$ to 0.894^{**}), and straw yield ($r = 0.833^{**}$ to 0.890^{**}), **(Saha *et al.,* 2014)**. These findings also confirm the critical role of P availability in influencing crop productivity and soil nutrient dynamics, which achieve the sustainable development goals.

As presented in Table 7, highly significant positive linear correlations (r) were observed between NPK uptake and wheat yield components. Additionally, the inorganic P fraction in the soil revealed a significant correlation with straw, grain, and total biological yield. A high positive relationship was identified between N, P, and K concentrations and yield components, as well as between available P and yield performance. These findings suggest that phosphate fertilizer particle size plays a crucial role in determining available P levels, ultimately influencing yield outcomes **(Soliman, 2025)**.

Table 3. Effect of particle size of ordinary superphosphate on wheat straw and grain yields and grain/straw ratio.

Treatments	Straw Yield	Grain Yield	Biological Yield	G/S Ratio
	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	
Whole fertilizer (T_1)	7.77 d ±0.21	6.46 d ±0.13	14.2 d ±0.25	0.835
1.0-0.5 mm (T_2)	10.9 a ±0.21	8.59 a ±0.12	19.5 a ±0.22	0.790
0.5-0.25 mm (T_3)	10.6 a ±0.27	8.13 b ±0.13	18.7 a ±0.32	0.770
0.25-0.125 mm (T_4)	9.78 b ±0.16	7.86 b ±0.16	17.6 b ±0. 28	0.803
< 0.063 mm (T_5)	8.45 c ±0.24	6.90 c ±0.12	15.3 c ±0.27	0.820
L.S.D $_{0.05}$	**0.65**	**0.35**	**0.77**	**ns**

The data represent the mean values of three replicates (n = 9) for each parameter with. Distinct letters indicate statistically significant differences among treatments, as assessed by the least significant difference (LSD) test at P ≤ 0.05 with standard error.

Table 4. Effect of particle size of rock phosphate on wheat straw and grain yields and grain/straw ratio.

Treatments	Straw Yield	Grain Yield	Biological Yield	G/S Ratio
	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	
Whole fertilizer (T_1)	6.23 c ±0.29	4.79 d ±0.23	11.0 d ±0.50	0.769
1.0-0.5 mm (T_2)	8.39 a ±0.17	6.64 a ±0.17	15.0 a ±0.30	0.794
0.5-0.25 mm (T_3)	8.05 ab ±0.17	5.94 b ±0.10	14.0 ab ±0.30	0.739
0.25-0.125 mm (T_4)	7.98 ab ±0.19	5.64 bc ±0.21	13.6 bc ±0.30	0.711
< 0.063 mm (T_5)	7.40 b ±0.31	5.28 cd ±0.17	12.7 c ±0.40	0.719
L.S.D $_{0.05}$	**0.68**	**0.52**	**1.02**	**ns**

The data represent the mean values of three replicates (n = 9) for each parameter. Distinct letters indicate statistically significant differences among treatments, as assessed by the least significant difference (LSD) test at P ≤ 0.05 with standard error.

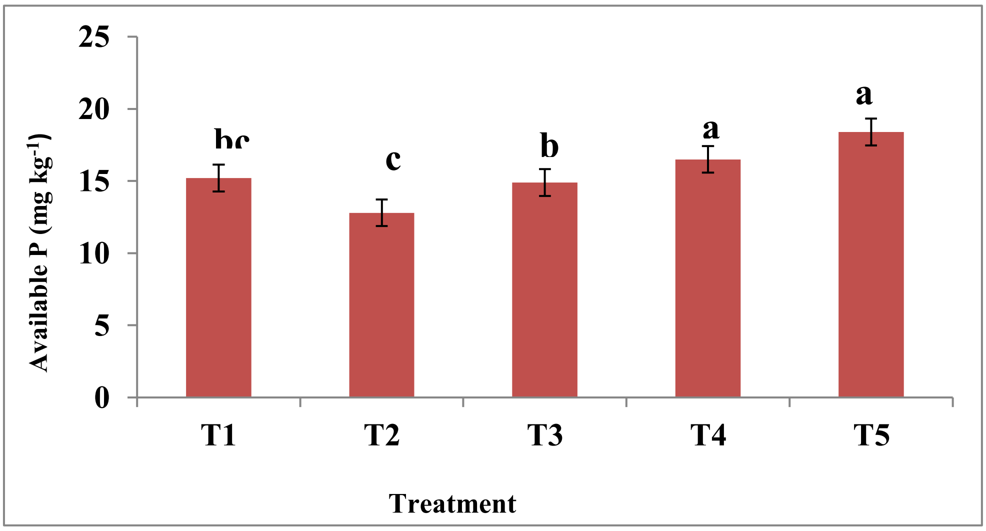

Fig. 1. Effect of particle size of ordinary superphosphate application on past-harvest available P (mg kg^{-1}) in soil cultivated with wheat. T_1, Whole fertilizer; T_2, 1.0 - 0.5 mm; T_3, 0.5 - 0.25 mm; T_4, 0.25 - 0.125 mm; T_5, < 0.063 mm. *Error bars* indicate the standard deviation of the mean values (n = 3), representing the variability within the data set.

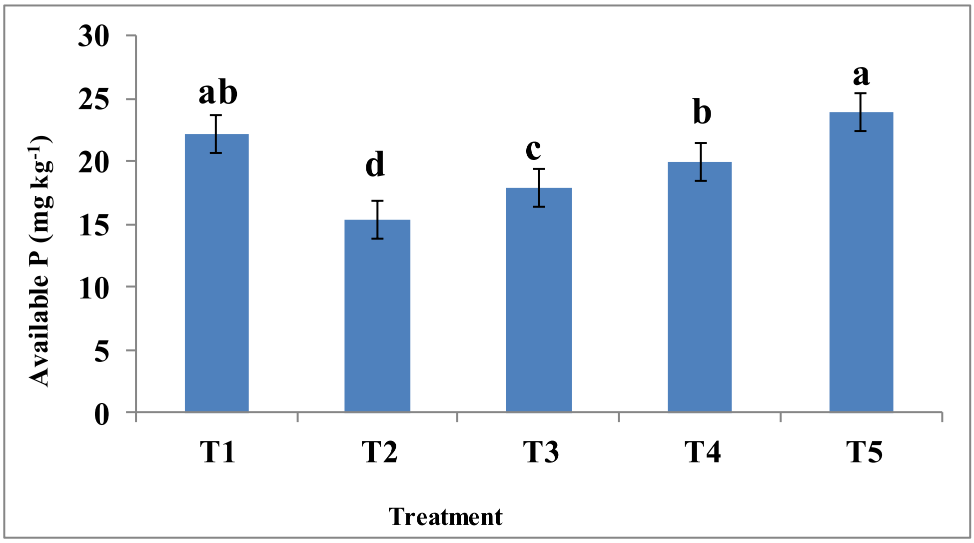

Fig. 2. Effect of particle size of rock phosphate application on paste-harvest available P (mg kg^{-1}) in soil cultivated with wheat. T_1, Whole fertilizer; T_2, 1.0 - 0.5 mm; T_3, 0.5 - 0.25 mm; T_4, 0.25 - 0.125 mm; T_5, < 0.063 mm. *Error bars* indicate the standard deviation of the mean values (n = 3), representing the variability within the data set.

Table 5. Effect of particle size of ordinary superphosphate application on the contents of N, P and K (g kg^{-1}) and uptake (kg ha^{-1}) in wheat grains.

Treatment	N		P		K	
	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Whole fertilizer (T_1)	28.4	183 e ±2.24	3.48	22.4 c ±0.28	13.5	87 c ±2.62
1.0-0.5 mm (T_2)	28.9	248 a ±2.75	3.96	34.0 a ±1.93	13.9	119a ±3.69
0.5-0.25 mm (T_3)	29.2	237 b ±2.93	3.69	30.0 ab ±1.52	13.8	112 ab ±3.59
0.25-0.125 mm (T_4)	28.9	227 c ±2.43	3.71	29.2 b ±1.13	13.8	109b ±1.86
< 0.063 mm (T_5)	29.0	200 d ±2.08	3.54	24.4 c ±0.37	13.4	92.6 c ±1.48
L.S.D $_{0.05}$	**ns**	**9.32**	**ns**	**4.50**	**ns**	**8.19**

The data represent the mean values of three replicates (n = 3) for each parameter. Distinct letters indicate statistically significant differences among treatments, as assessed by the least significant difference (LSD) test at $P \leq 0.05$ with standard error.

Table 6. Effects of particle size of rock phosphate application on the contents of N, P and K (g kg^{-1}) and uptake (kg ha^{-1}) in wheat grains.

Treatment	N		P		K	
	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Whole fertilizer (T_1)	29.6	142 c ±4.52	3.54	17.0 c ±0.92	13.8	66.0 c ±4.31
1.0-0.5 mm (T_2)	28.7	191 a ±4.27	3.68	24.4 a ±0.65	13.5	89.5 a ±2.23
0.5-0.25 mm (T_3)	28.7	170 b ±5.18	3.70	22.0 ab ±0.52	13.7	81.2 ab ±2.07
0.25-0.125 mm (T_4)	28.6	162 b ±5.90	3.55	20.0 bc ±1.64	13.7	77.1 b ±2.49
< 0.063 mm (T_5)	29.0	153 bc ±٣.26	3.55	18.7 bc ±0.60	13.7	72.5 bc ±1.23
L.S.D $_{0.05}$	**ns**	**19.7**	**ns**	**3.37**	**ns**	**8.83**

The data represent the mean values of three replicates (n = 3) for each parameter. Distinct letters indicate statistically significant differences among treatments, as assessed by the least significant difference (LSD) test at $P \leq 0.05$ with standard error.

Table 7. Correlation coefficients (r) between wheat yield components, N, P and K nutrients uptake and soil-available P.

Yield components	Nutrients uptake			Available P
	N	P	K	
Straw yield	0.997**	0.991**	0.988**	0.604**
Grain yield	0.883**	0.972**	0.921**	0.730**
Biological yield	0.964**	0.969**	0.983**	0.831**

** Significance at P<0.01

Comparison between ordinary superphosphate and rock phosphate fertilizers

The results obtained in Table 8 clarify the evaluation of the relationship between OSP and RP fertilizers, showing significant differences between the two fertilizers used for yield components and nutrients. The obtained results indicated that OSP treatments (for all diameters) significantly increased all wheat yield components (straw, grains, biological yield) when compared to RP treatments at the same diameters (Table 8). The same results were observed for nutrient uptake (NPK) in wheat grains. In contrast, RP treatments significantly increased soil available P (19.8 mg kg-1 soil) when compared to OSP treatments (15.6 mg kg^{-1} soil) after wheat harvesting. The findings that RP exhibited a stronger residual effect than OSP on soil available P suggest its potential for long-term soil fertility improvement. Fine phosphate particles resulted in higher levels of P remaining in the soil The slow-release nature of RP enhances long-term P availability. Additionally, both available soil P levels and soil acidity significantly influence plant responses to RP application. The higher amount of accumulated residual P in light -textured soils may increase the P movement below the rhizosphere **(Zhang *et al.,* 2023)**.

Table 8. Comparison between ordinary superphosphate and rock phosphate fertilizers for wheat yield components, grains nutrients uptake and soil available P.

Parameters	Type of fertilizer		L.S.D $_{0.05}$
	OSP	RP	
Grain yield (Mg ha^{-1})	7.59 a	5.66 b	0.357
Straw yield (Mg ha^{-1})	9.50 a	7.61b	0.515
Biological yield (Mg ha^{-1})	17.1 a	13.3 b	0.823
N (kg ha^{-1})	219 a	163 b	17.12
P (kg ha^{-1})	28 a	20 b	3.06
K (kg ha^{-1})	114 a	77 b	8.79
Available P (mg kg^{-1} soil)	15.6 b	19.8 a	2.40

Contextualizing findings within global issues

The global issue of climate change is closely tied to agricultural practices, particularly how nutrient cycles like P are managed. The increase in the yield of wheat and P availability due to the type of fertilizer and the effect of segregation particle size can be seen as a means of improving soil health and increasing food abundance, which is essential for sustainable agricultural systems. Maximum straw and grain yields were recorded for OSP (10.9 and 8.59 Mg ha^{-1}, respectively) and RP (8.39 and 6.64 Mg ha^{-1}, respectively). These agricultural practices play a significant role in minimizing the detrimental repercussions of climate change by enhancing food security while simultaneously reducing reliance on chemical fertilizers, which are a significant source of carbon emissions. Sustainability is at the heart of this research. The positive relationship between particle size and P availability illustrates how fine-tuning agricultural practices can yield better results in terms of both crop production and sustainability. In this study, the optimal particle size for phosphate fertilizer application was found to be between 1-0.5 mm and 0.5-0.25 mm, with improved wheat yield and phosphorus uptake under these conditions. These findings support the growing movement within the agricultural sector to adopt more sustainable and climate-resilient practices in response to the global challenges of soil degradation and climate change. The results of this study challenge conventional fertilizer application strategies, particularly regarding RP, by highlighting the efficacy of inoculating phosphate-solubilizing microorganisms in enhancing soil P availability. This approach reduces dependence on high quantities of synthetic fertilizers, promoting a more sustainable nutrient management system.

Conclusions

Improving the application of phosphate fertilizers, especially regarding different particle size, is essential to enhance wheat yields and improve P availability in loam sand soil. The obtained results of this research contribute valuable insights into effective agricultural practices, emphasizing the need to carefully manage fertilizers to meet the growing demand for food. Maximum straw and grain yields were recorded for OSP (10.9 and 8.59 Mg ha^{-1}, respectively) and RP (8.39 and 6.64 Mg ha^{-1}, respectively). The highest residual soil available P concentrations (18.5 mg kg^{-1} for OSP and 23.9 mg kg^{-1} for RP) were observed in treatments with <0.063 mm particles. Ordinary superphosphate resulted in greater nutrient absorption (248 kg ha^{-1} N, 34 kg ha^{-1} P, 119 kg ha^{-1} K) than RP, which showed lower but notable nutrient uptake (191 kg ha^{-1} N, 24 kg ha^{-1} P, 89.5 kg ha^{-1} K). As global food security remains an urgent concern, further investigation of the interactions between soil properties, fertilizer types and application practices will be critical in developing sustainable agricultural systems capable of meeting future challenges. Integrating these findings into practical farming strategies can significantly impact crop productivity and nutrient management, ultimately contributing to global food security. The optimal particle size for phosphate fertilizer application to wheat was between 1.0-0.5 mm and 0.5-0.25 mm. Applying phosphate fertilizer in these particle sizes, as part of the recommended dosage before planting, improves wheat yield, increases plant P uptake, and improves soil P availability. Given the high costs associated with fertilizing chemicals, using appropriately sized particles also boosts fertilizer efficiency in the soil. Optimizing the application of fertilizers, based on the research findings, can reduce both the financial burden on farmers and the environmental degradation caused by over-fertilization, aligning with sustainable agricultural practices and supporting climate action goals.

Recommendations

Application of phosphate fertilizers in a field experiment has shown that the optimal particle size of phosphate fertilizers (ordinary superphosphate and rock phosphate) when applied to wheat ranges between 1.0-0.5 mm and 0.5-0.25 mm. Applying phosphate fertilizer with this particle size, as part of the recommended pre-planting dose, improves wheat productivity, increases the plant P absorption, and enhances P availability in the soil. Due to the high cost of chemical fertilizers, using particles of the appropriate size also enhances the fertilizer's efficiency in the soil. Phosphate factory owners are recommended to manufacture these optimal sizes as advised by the study to achieve optimal production and reduce costs for farmers. This study contributes to sustainable global agricultural practices by addressing the vital aspects of the Sustainable Development Goals.

List of abbreviations:

P: Phosphorus
OSP: Ordinary superphosphate
RP: Rock phosphate
SAR: Sodium adsorption ratio
G/S: Grain/straw
N: Nitrogen
K: Potassium

Consent for publication:

All authors declare their consent for publication.

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The author declares no conflict of interest.

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